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EXPERIMENTAL STUDIES OF LOUDNESS AND ANNOYANCE RESPONSE TO SONIC BOOMS

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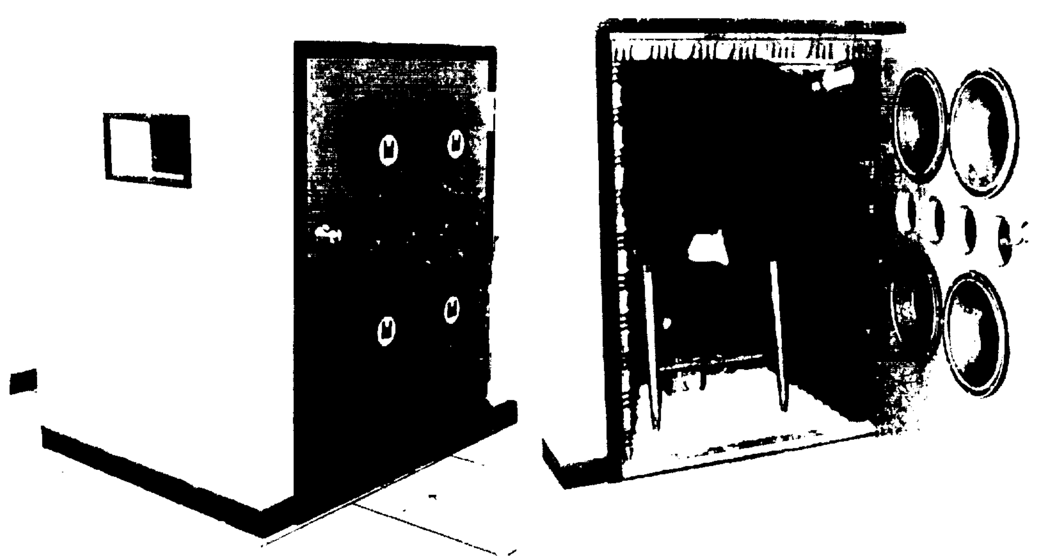
The purpose of this paper is to summarize the latest three sonic boom laboratory studies performed at NASA-Langley using the Sonic Boom Simulator. The first used synthesized idealized outdoor boom shapes which were filtered to represent booms heard inside a house. The test explored the efficacy of various metrics in assessing both loudness and annoyance responses to these booms. The second test investigated the effects of adding single reflections to idealized boom signatures, and the third compared booms recorded from real aircraft with idealized boom signatures to determine if subjects rated the real booms differently. In these studies, as in previous studies performed at NASA-Langley, there was a continuing effort to evaluate metrics for predicting the subjective effects of sonic booms.

OBJECTIVES

- Summarize recent lab studies
  - Quantify indoor/outdoor subjective effects
  - Determine effects of ground reflections
  - Quantify loudness response to recorded booms
  - Evaluate metrics

The tests were conducted using the NASA-Langley sonic boom simulator. The simulator is a person-rated, airtight, loudspeaker-driven booth capable of accurately reproducing user-specified waveforms with peak pressures of up to 138 dB. Signals are preprocessed to compensate for non-uniformities in the frequency response of the booth and sound reproduction system. The system is fully described in reference 1. Although tests using the Simulator cannot completely replicate conditions in real life, they allow listeners to evaluate sonic booms under controlled conditions.

SONIC BOOM SIMULATOR



A total of 168 subjects took part in the three tests: 72 in test 1, 48 in test 2 and 48 in test 3. Tests 2 and 3 were run concurrently and used the same subjects. Magnitude Estimation Scaling was the psychometric methodology used. In this methodology, one boom was selected as a reference and given a score of 100. Subjects were asked to compare all other booms to this reference on a ratio basis. The wave shapes used in the tests included simulations of the N-waves, front-shock minimized (shaped) booms, composite booms (that is, an original N-wave or minimized boom waveform, to which was added a single delayed copy of the original), and recorded booms, which were digitally recorded and modified for reproduction in the simulator.

EXPERIMENTAL APPROACH

- Three experiments
- Magnitude estimation scaling
- 168 test subjects
- Signature shapes
  - N-waves
  - Shaped
  - Composite (original + reflected)
  - Recorded

Five metrics have been studied in these and previous tests run at Langley. These were unweighted sound exposure level (SEL), A-weighted sound exposure level (SEL_A), C-weighted sound exposure level (SEL_C), perceived level (PL) using the Stevens' Mark VII procedure, and Zwicker loudness level. Considering the results of all tests run in the Simulator to date, PL has proved to be the most effective metric for predicting subjective reactions to sonic booms. Therefore the results of the three tests in the present paper are reported in terms of PL. Full details on the calculation procedures are given in reference 2. Previous tests are described in references 3, 4 and 5.

METRICS

- Five metrics considered
  - — SEL (unweighted)
  - — SELA
  - — SELC
  - — Perceived Level (Stevens' Mark VII)
  - — Zwicker Loudness Level
- All studies have evaluated metric performances
- Perceived Level selected as best metric for general use

The objectives of the first experiment were to investigate whether people respond differently to sonic booms heard indoors as compared with booms heard outdoors, to determine whether there would be a difference if they were asked to rate loudness or annoyance, and to validate the PL metric. Tests in the booth cannot be true simulations of reactions in the home, as there is no rattle, no fear of property damage, and the subjects' sole activity is to sit and listen to the booms. Hence this test could only compare loudness and annoyance responses in the lab. The test results do provide a basis for determining which descriptor was more appropriate and for evaluating which metrics predicted people's reactions most accurately. This test used two groups of 36 subjects each; one group was asked to rate the booms based on annoyance and the other was asked to judge loudness. Both groups heard the same signals played at the same levels; both used the same reference boom with a score of 100. The calculated metric levels were unchanged between the two parts of the test; only the subjective ratings differed.

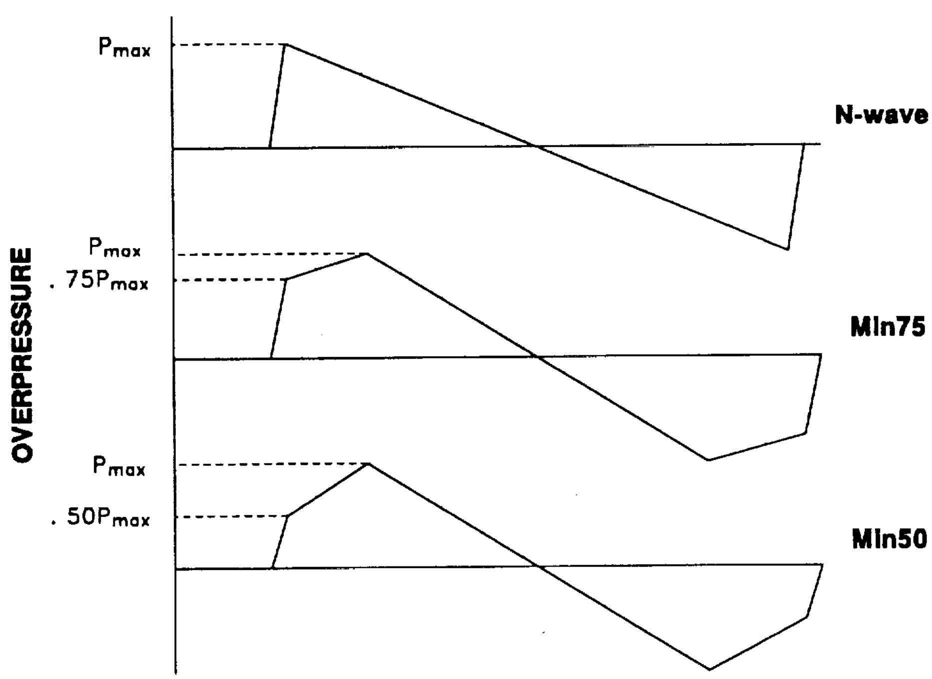
EXPERIMENT 1 OBJECTIVES

- Quantify loudness and annoyance of simulated indoor and outdoor booms
- Determine appropriate subjective criterion measure
- Verify PL metric

The signatures used in this study were based on three shapes: an N-wave, a front-shock minimized boom with a ratio of front shock to peak overpressure of 0.75 and a front-shock minimized boom with a ratio of front shock to peak overpressure of 0.5, as shown in the figure. The front-shock minimized (FSM) booms had a secondary rise time of 60 msec. All booms had a duration of 300 msec, and for all three shapes front-shock rise times of 2, 4 and 8 msec were used. Thus a total of nine waveforms comprised the outdoor signals.

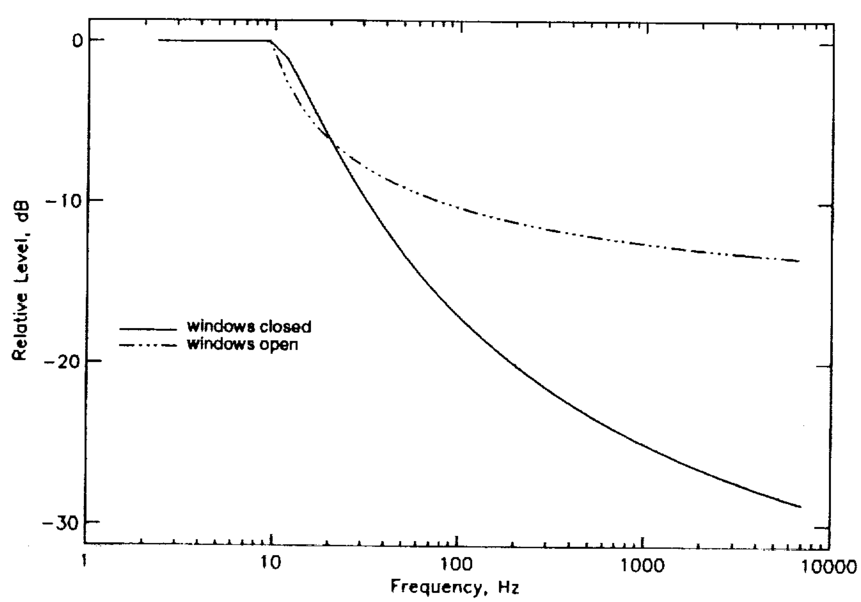
NOMINAL OUTDOOR SIGNATURES

(All durations = 300 msec)



Each outdoor shape was digitally filtered using two filters, one representing the attenuation through a typical house wall with windows open and the other with windows closed. Both gave no attenuation below 10 Hz, which is considered the simplest reasonable assumption in view of the lack of data at these frequencies. Above 60 Hz, these shapes were mathematical curves based on measured data. For both filters, the effect was to remove high frequency energy, more of which was removed by the "windows closed" filter than by the "windows open" filter.

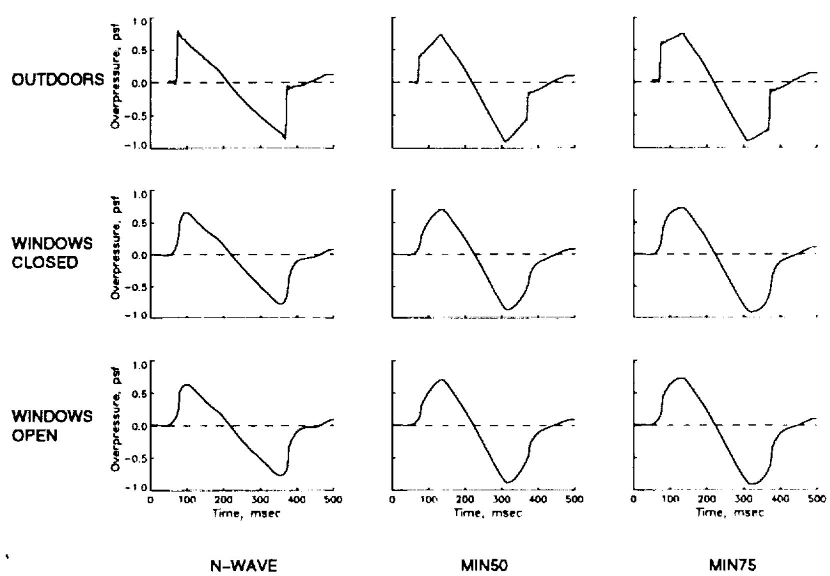
HOUSE FILTERS



This chart shows simulated indoor and outdoor booms, as measured within the simulator, for cases where the outdoor booms had rise times of 2 msec. Differences between the N-wave and the FSM booms can still be seen in the filtered shapes, but the high frequency, sharp corners of the originals have been greatly reduced. The nine original shapes were each presented to the subjects in the original form (the "outdoor" booms) as well as in the two "indoor" forms ("windows open" and "windows closed"). Measurements of sonic booms inside real houses would show more complex signatures, because of phase changes which were not simulated. However, these changes do not alter the frequency content of the boom. No reverberation effects were included in these simulations.

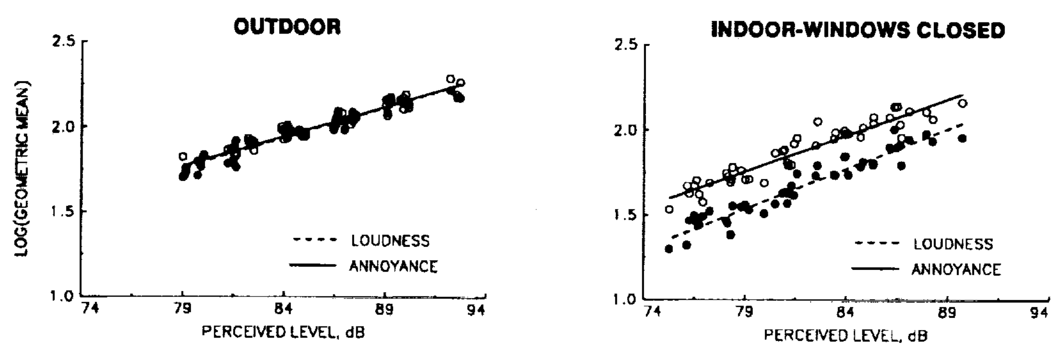
OUTDOOR AND INDOOR SIGNATURES

(rise time = 2 msec)



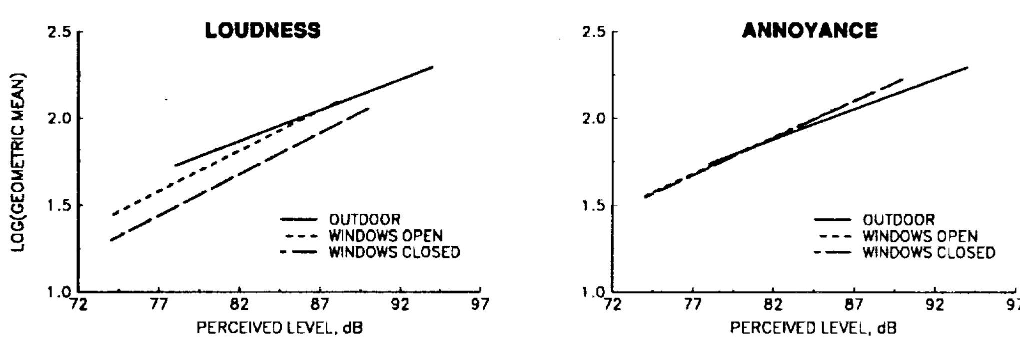
Results obtained in the first experiment are summarized in this chart which displays plots of the logarithm of the geometric means of the subjective ratings versus Perceived Level. The geometric mean is the appropriate central tendency measure for data obtained using the Magnitude Estimation psychometric method. For the outdoor booms, the results (displayed in the plot on the left) show no difference between loudness and annoyance responses, which agrees with previous studies. However, differences between loudness and annoyance scores were found for the indoor booms. For both simulated indoor conditions, the annoyance responses where higher than loudness responses. The plot on the right shows the results for the "windows closed" condition. The "windows open" results were similar, except that the differences between loudness and annoyance responses were smaller. This is reasonable since the "window open" filter had less effect on the boom than the "windows closed" filter. Statistically the slopes are not significantly different for either pair of lines. At the levels used in this test, the low frequencies were dominant in the indoor booms. Thus it could be inferred that they caused an increase in annoyance greater than their contribution to loudness. Based upon these results it is recommended that studies of indoor booms use annoyance rather than loudness as the judgement criterion, as the use of loudness may underestimate the booms' unacceptibility.

LOUDNESS AND ANNOYANCE RESPONSE



The performance of PL for judgements of loudness (left plot) and annoyance (right plot) for each simulated listening condition is shown in this figure. For a given PL value, the indoor booms were rated lower in loudness than the outdoor booms. The "windows open" condition lies between the outdoor and the "windows closed" loudness results. However, the indoor and outdoor booms of the same PL level were rated equally annoying. In both plots, the slopes of the regression lines for the indoor boom results differ significantly from those for the outdoor boom results. Results for SELA or the other metrics investigated (not shown) clearly indicate that PL predicted more accurately the annoyance for the combined data set of indoor and outdoor booms.

PL METRIC PERFORMANCE



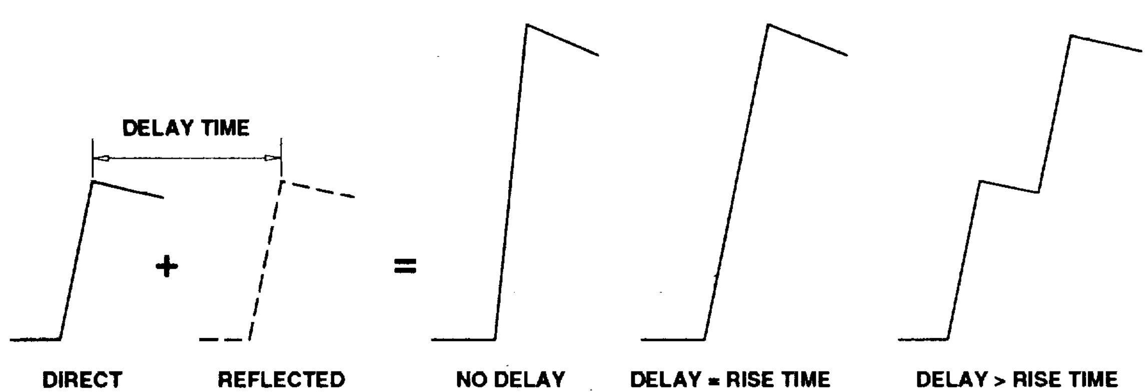
Field measurements of sonic booms are usually made with flush-mounted microphones, in which case a single reflection is present in the recording with a zero time delay between the direct boom and the reflected boom. However, outdoor listeners will usually receive a direct boom followed by a reflection off the ground having a finite delay, of the order of 8 msecs. In the second experiment, the objective was to evaluate the effects of different delay times on subjective response and to find a metric that accounted for these effects. To investigate this, single "reflections" were added to idealized boom shapes. Delay time between the "direct" boom and the "reflected" boom was a variable in this study. As only outdoor boom shapes were used, subjects were asked to rate loudness.

EXPERIMENT 2 OBJECTIVES

- Quantify loudness of sonic booms containing reflections (direct + single reflection)
- Determine delay time effects
- Verify PL metric

This chart demonstrates the effect of adding to an idealized N-wave shape (the "direct" boom) a single time-delayed version of the same shape (the "reflected" boom). The combined wave form is called a "composite" boom. No phase change or attenuation was introduced into the delayed wave. If the delay is zero, the result of combining the direct and reflected booms is a doubling of overpressure while the rise time remains unchanged. If the delay is equal to the rise time, the resulting wave has a rise time twice that of the original, while the overpressure is nearly double the original. Other delay times result in composites having complex, multi-segmented pressure increases.

COMPOSITE BOOM SIMULATION



DIRECT + REFLECTED = COMPOSITE

The basic shapes considered were an N-wave and a front-shock minimized boom with a ratio of front shock overpressure to peak over pressure of 0.5. For both shapes rise times of 3, 6 and 9 msec were used, which resulted in six waveforms for the "direct" booms. For each direct boom, six values were selected for the delay time. Delays of 0 msecs and 12 msecs were used for each direct boom. A value of delay equal to the front shock rise time was also selected, together with rise time + 1 msec and rise time − 1 msec. The sixth value of the delay was 3 msecs, except for the booms with 3 msec rise times, where a value of 8 msec was used.

EXPERIMENTAL WAVEFORMS

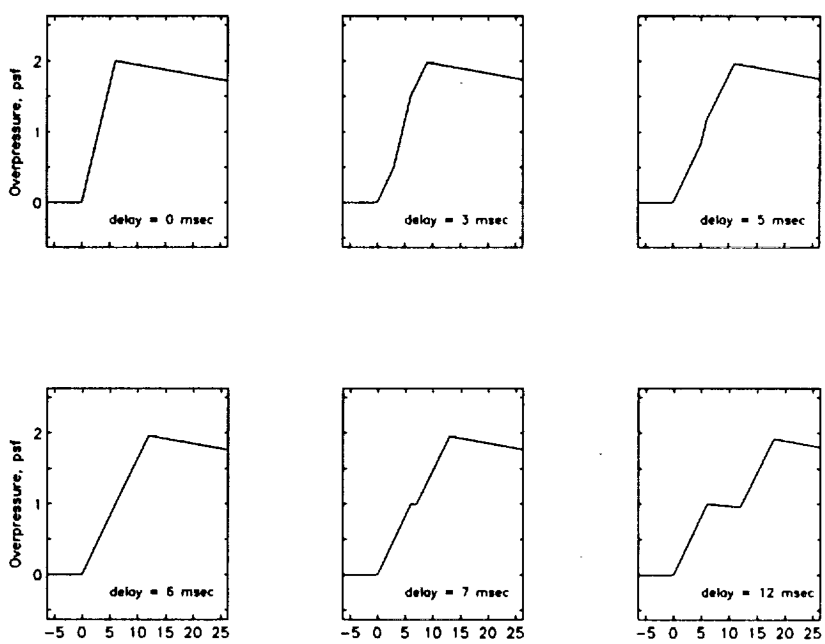
- Six direct boom waveforms
  - — 3 N-waves (rise times = 3, 6, 9 msecs)
  - — 3 shaped (front shock rise times = 3, 6, 9 msecs)

- Six reflection delay times for each direct boom

The composite waveforms that resulted when a 6–msec N-wave was used as the original waveform are illustrated here. In these idealized plots, the direct boom has an overpressure of 1 psf. The delay time between the "direct" boom and the "reflection" was varied between 0 and 12 msec. The zero delay results in a waveform with a rise time of 6 msec, but a peak overpressure of 2 psf. When the delay equals 6 msec, the composite wave has a peak overpressure of almost 2 psf, but the rise time has been doubled to 12 msec. The other delays produce other more varied waveshapes.

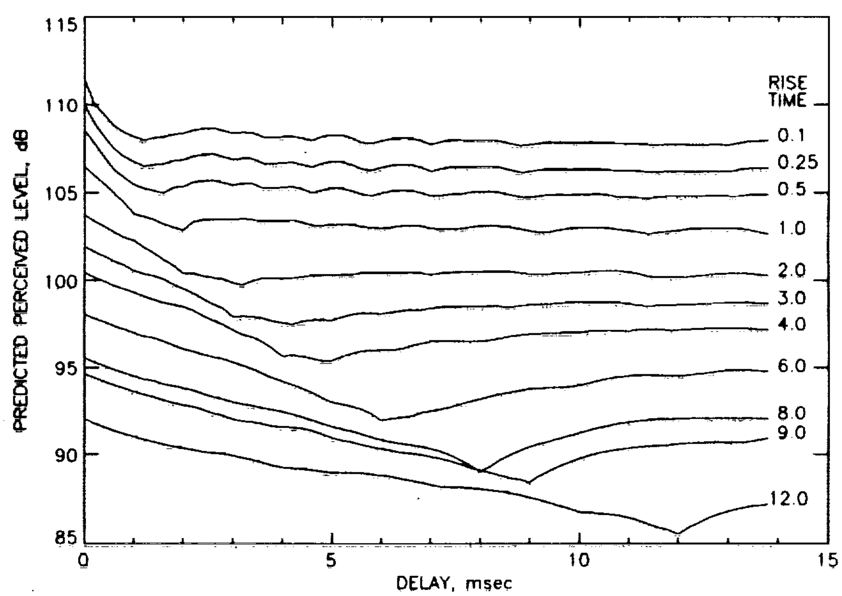
COMPOSITE WAVEFORMS

(N–wave, τ = 6 msec)



The effects of varying the delay for booms with a range of rise times were predicted using the PL metric. This chart shows the predicted PL values for N-waves with rise times ranging from 0.1 msec to 12 msec, and delays from 0 to 14 msec. The curves show a maximum at zero delay, and a minimum for most cases when the delay equals the rise time. Some of the irregularities in these curves are due to the fact that they were calculated using 1/3 octave bands. As the delay time changes, there are subtle changes in the spectrum, which cause energy to shift in frequency. As it shifts from one band to another, there are changes in the calculated values. If a continuous algorithm is used, such as that used for SELA, these irregularities are removed. SELA shows the minimum when the delay exactly equals the rise time, but for the short rise times PL shows the minimum at somewhat greater delays. This is probably an artifact of the calculation procedure.

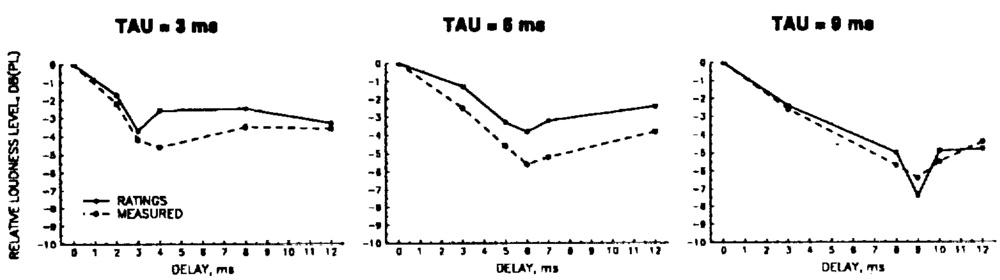
PREDICTED DELAY TIME EFFECTS



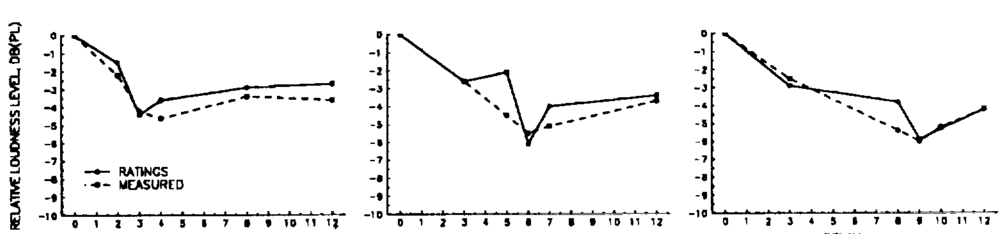
This chart shows the results obtained for the six basic waveforms, each with six different delay times. The solid lines show the subjective responses, converted to equivalent PL, while the dashed lines show PL calculated from the measured data. The results are normalized to 0 dB at a delay time of zero. In general there is good agreement between PL calculated from measurement and PL derived from the ratings. The ratings all show a minimum when the delay time is equal to the boom front shock rise time. Predicted PL and PL based upon measurements also gave minima when delay time equals front shock rise time except for the 3 msec booms which have a minimum at a 4 msec delay.

Most sonic boom measurements are made with flush-mounted microphones, for which there is zero delay between the direct wave and the ground-reflected wave. Hence, these measurements will yield loudness levels that are conservative compared to outdoor situations, where the listener will experience a ground reflection with a delay typically of the order of 8 msec. In an enclosed situation, there could be more than one reflection, and more complex wave forms could result.

DELAY TIME EFFECT



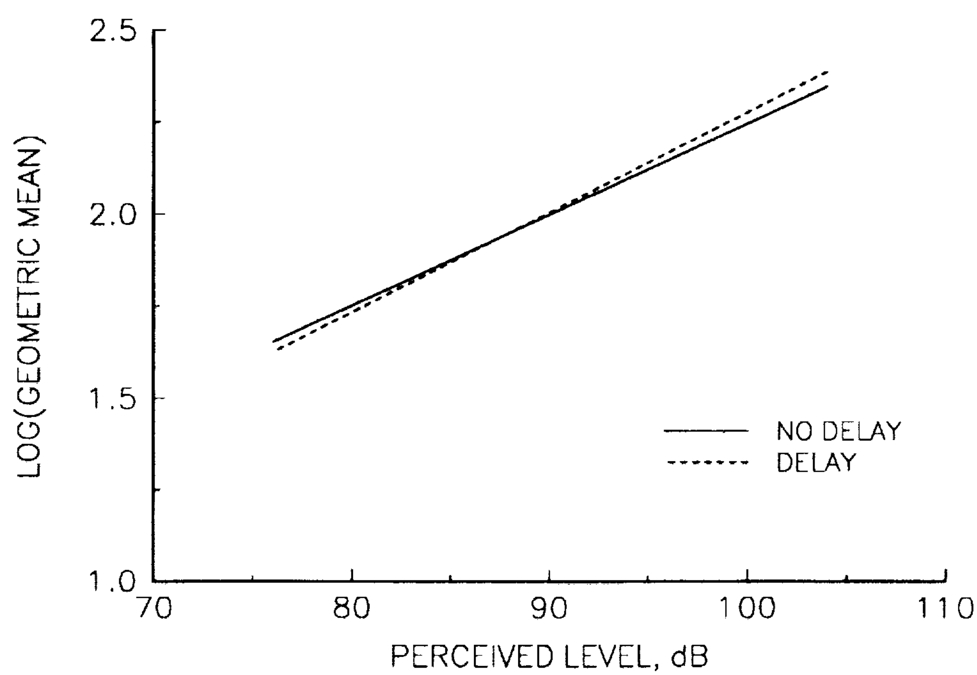
N-waves



Shaped Booms

The figure shows a plot of subjective ratings as a function of PL calculated from measured data for the set of composite booms containing reflections with zero delay and for the set containing reflections with non-zero delays. There is no statistically significant difference between the two lines, and PL can be said to account for the effects of delay on loudness.

DELAY EFFECT - PL METRIC



The third experiment used real sonic boom recordings made at White Sands Missile Range from T38 and F15 flyovers. The objective of the test was to determine if people reacted differently to real booms as compared to idealized booms, and to assess metric performance for predicting the loudness of real booms that have been distorted by propagation through the atmosphere. The recordings were made using the United States Air Force's BEAR (Boom Event Analysis Recorder) systems using a 8 kHz sample rate. Seven hundred recorded signatures were scanned and thirteen booms selected that fitted into four major categories of sonic boom shape:

1. N-wave
2. Rounded
3. Peaked
4. U-shaped

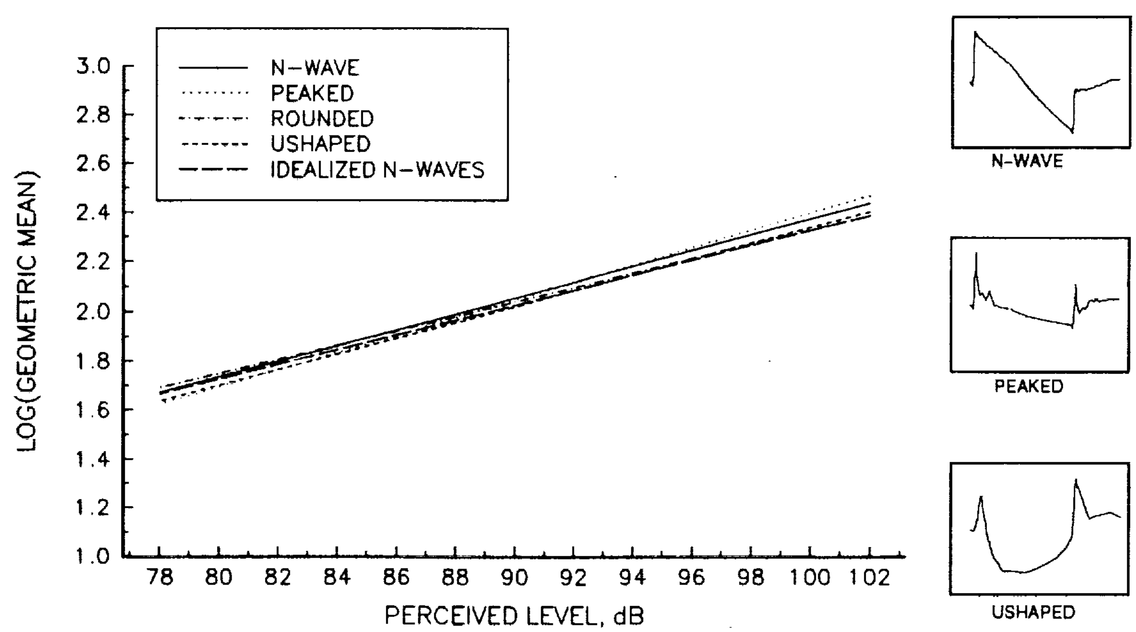
The recorded booms were digitally edited to remove some of the background noise and to increase the time between their front and rear shocks to 300 msec, which is more representative of a HSCT. The front and rear shocks were not altered by this procedure. Three idealized N-waves and two boom shapes based on predictions for HSCT from various CFD codes were also included, resulting in a total of 18 signals. The waveforms based on the CFD predictions were simplified, but both contained more than two pressure peaks. Because of the existence of extra shocks between the front and rear shocks, these were designated "intermediate" booms. All the signals, recorded and idealized, were preprocessed to account for the booth frequency response.

EXPERIMENT 3 OBJECTIVES

- Quantify loudness of recorded signatures
- Compare with results for idealized booms
- Verify PL metric

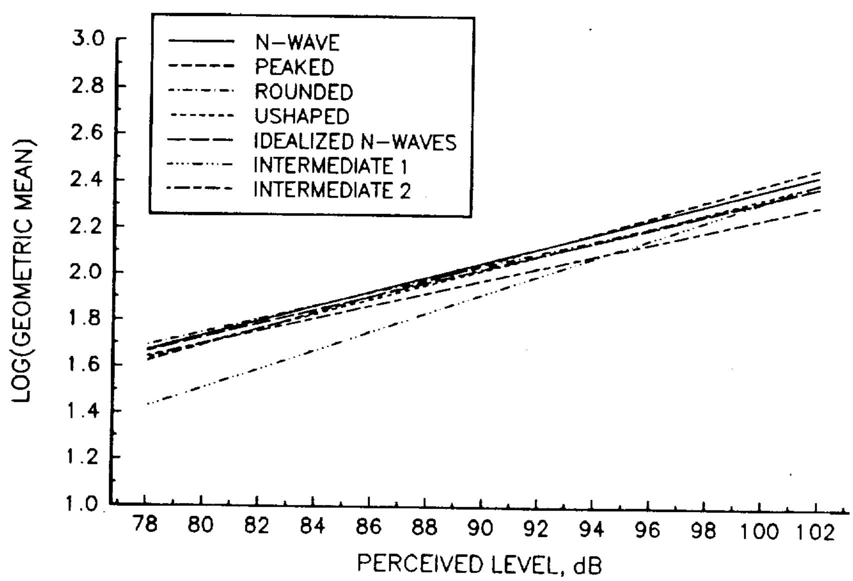
This chart presents some of the results from this test, together with three examples of the recorded waveforms as reproduced in the simulator. These data show that responses to the four categories of real booms did not differ from responses to the idealized N-waves when plotted against PL calculated from measured signals. Thus PL accounted for any differences between the waveforms. These booms were not played at the same levels as they were heard at White Sands, nor even at the same relative levels; instead they were adjusted to cover the same range of SEL_A values.

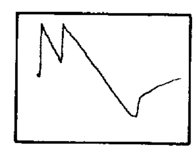
RESPONSE TO WHITE SANDS BOOMS



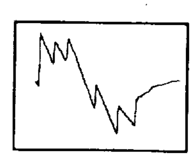
The only category of boom that stood out in this study were the "intermediate" booms. Time histories of these waveforms measured in the simulator are shown on the right of this chart. The plot displays the same judgement data as the previous chart, but the results for the two intermediate booms have been added separately. The intermediate boom results fall somewhat below those for the other boom categories, indicating that the subjects rated them as having lower loudness than the PL metric predicted. The slopes of the regression lines for the intermediate boom results differ from those for the other booms. Boom asymmetry is a possible contributing cause, though a previous study on asymmetry (reference 3) would predict little effect for Intermediate 1 and none at all for Intermediate 2. The multiple peaks may have some masking effect on each other. Further study is needed to understand these results, which were based on only two samples.

RESPONSE TO INTERMEDIATE BOOMS





INTERMEDIATE 1



INTERMEDIATE 2

In summary the findings of the three studies showed that loudness and annoyance gave equivalent results for outdoor booms but differed for indoor booms. Annoyance is therefore recommended as the most appropriate criterion for indoor boom judgements. For booms containing a single reflection, the loudness ratings were higher when the delay between the direct and reflected booms was zero than when the delay was greater than zero . Hence loudness values calculated from flush-mounted microphone measurements will be conservative. Subjects did not judge recordings of real booms any differently from idealized booms. The PL metric was validated for annoyance ratings, for indoor and outdoor booms, for booms with reflections and for real booms compared with idealized simulations.

SUMMARY

- Loudness and annoyance are:
  - — equivalent for outdoor booms
  - — not equivalent for indoor booms
- Annoyance most appropriate criterion
- Booms with single reflections are
  - — less loud for nonzero delay times
  - — Hence measurements with flush-mounted microphones are conservative
- Real booms not judged differently from idealized booms
- PL metric validated

References

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